LA-3783

78

AD663571

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Cross Sections for Electron Excitation of the 3914-Å (0,0) Band of the N_2^+ First Negative System

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

15

BEST
AVAILABLE COPY

ACCESSION for	
CFSTI	WHITE SECTION ☐
DDC	BUFF SECTION ☐
UNANNOUNCED	☐
JUSTIFICATION	
DISTRIBUTION/AVAILABILITY CODES	
DIST.	AVAIL. and/or SPECIAL

Printed in the United States of America. Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

LA-3783
UC-34, PHYSICS
TID-4500

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Report written: August 1967

Report distributed: December 29, 1967

Cross Sections for Electron Excitation of the 3914-Å (0,0) Band of the N_2^+ First Negative System*

by

Redus F. Holland

*Work done under the auspices of the AEC in response to ARPA Work Order No. 631, Program Code No. 5820.

CONTENTS

BLANK PAGE

CROSS SECTIONS FOR ELECTRON EXCITATION OF THE 3914-Å (0,0) BAND OF THE N_2^+ FIRST NEGATIVE SYSTEM

by

Redus F. Holland

ABSTRACT

As part of a study of the emission from nitrogen excited by an electron beam, cross sections for electron excitation of the 3914-Å (0,0) band of the N_2^+ first negative system were measured for electron energies of 95 to 2023 eV. Because published values for these cross sections differ by factors of two to three,[2,3,6] an effort was made to establish the accuracy of the measurements. 3914-Å band intensity was measured with two independently calibrated photometers and a scanning spectrometer. A comparison of equipment and joint observations were made with experimenters from two other laboratories. The cross section obtained for the 3914-Å band at 95 eV is 1.5×10^{-17} cm^2, and that at 2023 eV is 3.1×10^{-18} cm^2. By a simple calculation, one can derive a corresponding efficiency of 4.3×10^{-3} for the production of the 3914-Å band by electrons in air. The excitation cross sections are in reasonable agreement with other recent measurements,[6-8] but are higher than some values reported earlier.[2,3] The calculated efficiency is in fair agreement with the results of laboratory efficiency measurements.[10,11]

INTRODUCTION

A prominent feature of the emission spectrum of air or nitrogen ionized by electrons is the 3914-Å (0,0) band of the N_2^+ first negative system. The probability of exciting this band by electrons is of interest in the study of aurorae and related atmospheric phenomena and, in this Laboratory, as part of the general problem of describing the excitation of air by photoelectrons produced by thermal x rays from nuclear explosions. The excitation probability of the 3914-Å band has specific importance, as well, since observation of this band is the basis of the Los Alamos air fluorescence system for detecting nuclear events.[1]

Electron excitation cross sections for the 3914-Å band were first determined by Stewart,[2] and subsequent measurements include those of Sheridan, Oldenberg, and Carleton;[3] Hayakawa and Nishimura;[4] Davidson and O'Neil;[5] McConkey and Latimer;[6] Srivastava and Mirza;[7] and McConkey, Woolsey, and Burns.[8]

The observations of Sheridan, Oldenberg, and Carleton[3] covered a wide electron energy range (about 25 eV to 28 keV). Their results showed good agreement with Stewart,[2] Hayakawa and Nishimura,[4]

and Davidson and O'Neil[5] in their common energy ranges. The cross sections of McConkey and Latimer,[6] however, were a factor of 2 to 3 higher than those of Stewart[2] and Sheridan et al.,[3] in the same energy range.

The difference between the results of McConkey and Latimer and those reported earlier has been the subject of some discussion in the literature. Based in part on the cross sections of McConkey and Latimer,[6] Dalgarno, Latimer, and McConkey[9] estimated an efficiency of 4.0×10^{-3} for the production of 3914-Å band energy by energetic electrons in air, in fair agreement with the efficiency of 3.3×10^{-3} measured for 750-eV electrons by Hartman and Hoerlin.[10,*]

Commenting on the note of Dalgarno et al., Davidson[12] directed attention to the good agreement of the earlier cross-section measurements.[2-5] He pointed out that the data of McConkey and Latimer were taken with an indirectly calibrated system, while the earlier workers used standard lamp (photometric) calibrations.

McConkey, Woolsey, and Burns,[8] to check the validity of the technique used by McConkey and Latimer, have measured 3914-Å cross sections using a standard lamp calibration. They obtain cross sections in good agreement with those of McConkey and Latimer. Support for the "high" values is also provided by the recent measurements of Srivastava and Mirza.[7]

In this Laboratory, experiments have been in progress to measure the vacuum ultraviolet emission from nitrogen excited by an electron beam. Concurrent with these measurements, the intensity of light emitted in the 3914-Å band was measured, and excitation cross sections were determined for electrons with energies of 95 to 2023 eV. Initial values agreed very closely with the results of McConkey and Latimer.[6] Because of the interest in a precise determination of the 3914-Å band cross sections, an effort was made to reduce the probability of error, particularly that which might arise in the photometric calibrations. Multiple observations were made with two photometers and a scanning spectrometer, calibrated independently for absolute sensitivity. The proportionality of light output to beam current and nitrogen pressure was checked for some electron energies. The intensities of the N_2^+ first negative (0,0), (0,1), (0,2), and (0,3) bands were compared.

A cross check of pressure gauges and photometric standards was performed with R. O'Neil of American Science and Engineering (ASE) and N. P. Carleton of the Smithsonian Astrophysical Observatory. Joint observations with O'Neil of the 3914-Å cross section were made at one electron energy, using our electron beam source.

The experimental arrangements, calibration techniques, and results of these measurements are described below.

EXPERIMENTAL PROCEDURE

General

The experimental procedure was straightforward. A beam of electrons was directed across a chamber through which nitrogen was flowing, and collected on the opposite side. Light emitted passed through a Pyrex window, and its intensity was measured with a photometer or scanning spectrometer. From the intensity of emission, beam current, and gas density, cross sections for electron excitation were determined.

Apparatus

The gun and collision chambers and the 3914-Å photometer are shown in Fig. 1, as viewed from the top. The chamber is a 12-in. cube. Matheson prepurified N_2 gas, specification 99.996% pure, was admitted through a needle valve at the top. The gas inlet was baffled by a 1-in.-diam plate, 1/4 in. from the opening. Pressure was regulated by the inlet valve and a 4-in.-diam exhaust valve at the bottom of the chamber. The opening to the exhaust valve was baffled by a 10-in.-square plate, to aid in producing a uniform gas density. Gun and collision chambers were each equipped with a 720 liter/sec diffusion pump, trapped with liquid nitrogen. Lowest pressure obtained with no gas flowing in was

*Hartman[11] has recently repeated this measurement, obtaining an efficiency of 3.4×10^{-3}.

about 2×10^{-7} Torr. During measurements the gas flow rate was of the order of 0.03 Torr - liter/sec. The pressure in the chamber was monitored with an ionization gauge and measured with a McLeod gauge, both with apertures at the top of the chamber.

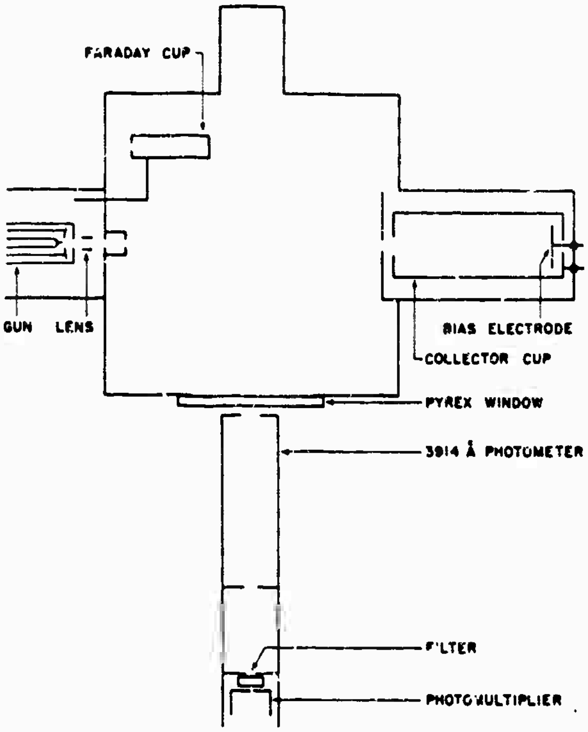

Fig. 1. Collision chamber.

The electron beam was produced by a triode gun and focused by an electrostatic lens, to pass through a first aperture of 3/16-in. diam and a second of 1/8-in. diam into the chamber. After traversing the chamber, the beam passed through a 1/2-in. hole in a grounded plate and through a 3/4-in. hole into a collector cup, 8 in. deep. To aid in collection of electrons, the collector cup was normally held at 5 to 7 V positive, and at the back had a plate biased at + 45 V. The beam current was measured at the collector and at an auxiliary cup which could be swung in front of the gun port.

Collision chamber, gun, and collection assemblies were made of nonmagnetic materials. The local magnetic field was initially about 0.6 G, and approximately perpendicular to the beam. Two 4-ft-diam coils were placed with planes at right angles to each other intersecting on the beam axis. Adjusting the current in these coils reduced the magnetic fields in the collision chamber to < 0.1 G, so that the beam traversed the chamber without noticeable bending.

The photometer collimator was a cylindrical tube with two rectangular apertures defining the field of view. In the first collimator used, the front aperture was 1/2 in. square, the back 1/8 in. square. The two were 12 in. apart. Mounted behind the back aperture was a 3914-Å interference filter and an EMI 6097S photomultiplier. A second photometer used was very similar to the one described.

The spectrometer was a half-meter Jarrell-Ash Ebert scanning monochromator, with 600 ℓ/mm grating blazed for 7500 Å. An EMI 6097S photomultiplier was mounted at the exit slit.

For both the spectrometer and photometer, tube currents were measured with a Keithly 610 electrometer.

Observational Arrangements

The photometer was placed with its axis perpendicular to the beam, and with two sides of each aperture parallel to the beam. The rectangular cone viewed by the photometer was about 1 in. wide at the beam. The cone extended into a recess at the opposite side of the chamber which was provided for attachment of a vacuum ultraviolet spectrometer, but which was terminated by a black plate during cross-section measurements.

In the measurements made with the Ebert spectrometer, the light emerging through the Pyrex window was focused on the entrance slit of the spectrometer by a 6-in. spherical mirror with 1-m radius of curvature. Distance from beam to mirror was 78.5 in., and that from mirror to spectrometer 26.5 in. The angle between incident and reflected beam was about 2°. The image of the beam was perpendicular to the entrance slit.

Photometer Calibrations

Two methods were used to calibrate photomultipliers for the 3914-Å photometer.

In the first method,* the tube sensitivity was determined by comparing its response to monochromatic light with that of a thermopile which had been calibrated with an NBS total irradiance standard. The comparison was indirect. Light from a Perkin-Elmer double monochromator was passed through a glass plate set at 45° to the axis and focused on the thermopile. The light diverted by the plate struck a frosted glass window behind which was a 1P28 photomultiplier. The ratio of 1P28 signal to power measured by the thermopile was determined. The intensity was reduced, and the thermopile replaced by the tube to be calibrated. The sensitivity of the tube is the ratio of its current to the beam power as determined from the 1P28 signal. The sensitivity at 3914 Å obtained with the tube used in photometer No. 1, EMI 6097S #23873, was 1.31×10^3 A/W at 750 V.

In the second method, the assembled photometer, i.e., the photomultiplier and interference filter mounted in the collimator tube, was exposed to filtered light from an NBS spectral irradiance standard. The external filters were a neutral density filter to reduce intensity, and a Corning 5113 filter to block the red leak of the interference filter.**

From the output signal, filter transmission curves, and lamp characteristics, the tube sensitivity at 3914 Å was determined. For the tube used in photometer No. 2, EMI 6097S #16747, the sensitivity at 3914 Å as determined by the first method was 420 A/W, and that determined by the second method, 390 A/W, at 750 V. The mean, 405 A/W, was used in data reduction.

To complete the photometer calibration, the effective transmission of the interference filter for the 3914-Å band, T_{eff}, was calculated from the filter transmission and a band contour calculated assuming a rotational temperature of 298° K. The two 3914-Å filters used were nearly identical. Each has a peak transmission of about 0.[illegible] at 3913 Å, and a half-width of ~ 14 Å. For each, $T_{eff} = 0.313$. Transmissions of all filters were measured with a Cary Model 14 spectrometer. The maximum divergence of the light from the axis of the spectrometer beam was estimated at 2.5°.

Spectrometer Calibration

For the calibration of the Ebert spectrometer, the ribbon filament of a standard lamp was placed, relative to the spectrometer and mirror, at the same position occupied by the electron beam in the cross-section measurements. Entrance and exit slits were 100 µ wide, and were masked to heights of ~ 2 and 4 mm, respectively. The image of the filament filled the entrance aperture. The current from the photomultiplier tube was recorded while the spectrometer was scanned from 3000 to 12,000 Å. The first and second orders appeared as two overlapping "humps," peaking at ~ 5000 Å in the first order and ~ 4000 Å in the second. Four runs were made, using two standard lamps.

For the first two scans, NBS brightness temperature standard lamp No. G-25155a was operated at brightness temperatures of 2200° and 2600° K. The spectral radiance for the two temperatures had been calculated using the tungsten emissivity data of de Vos[13] and taking into account the quartz window of the lamp.

Two scans were made with lamp No. U-111, an NBS spectral radiance standard, operated at 35.0 A (~ 2260° K brightness). During one run, a Corning 3389 filter was inserted to cut off light below 4000 Å. A comparison of results obtained with and without filter indicated that the contribution to the signal in the range 3750 to 4000 Å from scattered light with wavelength greater than 4000 Å was negligible. Also, in the second order above 3750 Å, the first-order contribution to the signal could be neglected.

The spectrometer sensitivity, expressed as the ratio of photomultiplier signal i_λ (A) to the product of lamp radiance R_λ (W cm^{-2} ster^{-1} Å^{-1}) and the entrance slit height h_n (cm), is shown in Fig. 2. The two runs with lamp G-25155a had a maximum spread of 6% and an average spread of 2%. Their mean is

*This measurement was performed by Walter Gould of this laboratory.

**During cross-section observations, a Corning 3389 filter which cuts off wavelengths below 4000 Å was used to check for a red contribution to the signal. None was observed.

the solid line in the figure. The black dots represent the values obtained with lamp U-111, determined at the NBS calibration points.

Pressure Measurement

Pressure in the collision chamber was measured with a Consolidated Vacuum Corporation GM-110 McLeod gauge, trapped with dry ice. Problems arising with such a system have been reviewed by Carr.[14]

The conventional way of operating the gauge may produce wrong pressure readings if the surface characteristics of the open and closed capillaries are different. In the method used, the open capillary was ignored, and the level of the mercury in the large, open side arm was used for reference. The capillary depression was measured at low pressure, as a function of the mercury level in the closed capillary. In each pressure measurement, the compression was varied to produce several pressure readings, as in the method of Podgurski and Davis.[15] The readings at each pressure usually agreed within 2 to 3%, for measurements in the range 0.05 to 3.0 μ Hg.

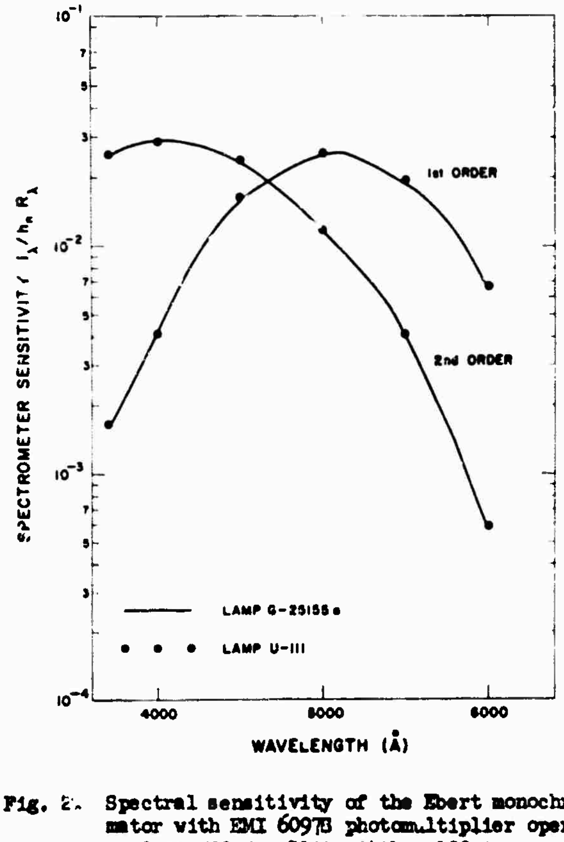

Fig. 2. Spectral sensitivity of the Ebert monochromator with EMI 6097B photomultiplier operated at 750 V. Slit widths, 100 μ.

At the lower end of the range, appreciable error can be caused by the diffusion of mercury from gauge to cold trap.[14] To reduce the vapor pressure and make this error negligible, the McLeod gauge was operated at 0° C. This made necessary a thermal transpiration correction of $(298/273)^{1/2} = 1.045$ to the measured pressure.

Beam-Current Measurement

At the pressure (~ 0.5 μ) of the energy-dependence measurements, beam currents measured at the entrance and exit collectors agreed within 1 to 2% for electron energy above 200 eV. The entrance collector current was normally about 6 to 8% higher for 200-eV and 10 to 12% higher for 100-eV electrons at this pressure. This must, in part, have been due to scattering out of the beam in the long (30-cm) path. At low pressure, ~ 0.13 μ, the agreements at 100 eV and 200 eV were ~ 5% and ~ 3%, respectively. Since the entrance and exit collector currents represent the maximum and minimum number of electrons crossing the detector field of view, the mean of the two current readings always was used in the calculations.

Electron Energy

The electron energy was assumed to be equal to the accelerating voltage, measured between the chamber and the gun filament leads. A crude retarding potential analysis made at low pressure, with 20 ℓ/in. screens over the apertures of the collector cup and shielding plate, indicated energy spreads of 3, 4, 5, and 10 eV for accelerating voltages of 95, 399, 704, and 1008 V, respectively. At the pressures of the cross-section measurements, there is some electron energy loss by collisions. The energy loss is not expected to change the light output significantly. The collisions may remove electrons from the field of view, as indicated above.

OBSERVATIONS AND RESULTS

Photometer Measurements

For the observations with the photometers, the cross section Q (cm²) for exciting the 3914-Å band

is given by

$$Q = \frac{i\, 4\pi R^2}{INE_\lambda\, \Delta\ell\, A\, T_w\, T_{eff}\, S_\lambda},$$

where

i = photomultiplier anode current (A)

R = distance from beam to back aperture (cm)

I = beam current (A)

N = N_2 number density (cm^{-3})

E_λ = energy of the photons $\cong$ 3.17 eV

$\Delta\ell$ = length of beam "seen" by a point on the back aperture (cm)

A = area of the back aperture (cm^2)

T_w = Pyrex window transmission = 0.92

T_{eff} = effective transmission of the interference filter for the 3914-Å band = 0.313

S_λ = tube sensitivity near 3914 Å (A/W)

Data and cross sections are presented below for energy-dependence measurements with two photometers.

For observations with photometer No. 1,

R = 51.0 cm

N = P (μ Hg) × 3.22 × 10^{13}

$\Delta\ell$ = 2.13 cm

A = 0.1008 cm^2

S_λ = 1.31 × 10^3 A/W at 3914 Å (6097S #23873 at 750 V)

$$Q\ (cm^2) = \frac{i\ (A)}{I\ (A)\ P(\mu)} \times 3.35 \times 10^{-12}$$

Results are shown in Table I.

Table I. Energy Dependence of 3914-Å Cross Sections with Photometer No. 1

Electron Energy (eV)	Nitrogen Pressure P(μ Hg)	Beam Current I(mA)	Tube Current i(10^{-8}A)	Cross Sections Q($10^{-17}cm^2$)
95	0.44	0.075	0.124	1.48
196	0.44	0.215	0.325	1.36
501	0.44	0.605	0.60	0.89
907	0.44	1.06	0.68	0.57
1820	0.44	1.65	0.63	0.34

Using photometer No. 1, the 3914-Å light output from 907-eV electrons was observed while pressure was held at 0.14 μ Hg and the gas flow rate was varied by first fully opening the exhaust valve, then closing it until the O-rings touched the sealing surface. The excitation cross section did not change. At electron energies of 197 and 907 eV, and pressure ~ 0.5 μ Hg, the collector cup bias was varied from 5 to 22 eV. No change in 3914-Å light output was observed.

For observations with photometer No. 2,

R = 71.8 cm

N = P (μ Hg) × 3.22 × 10^{13}

$\Delta\ell$ = 2.56 cm

A = .0495 cm^2

S_λ = 405 A/W (6097S #16747 at 750 V)

$$Q\ (cm^2) = \frac{i\ (A)}{I\ (A)\ P\ (\mu)} \times 4.30 \times 10^{-11}$$

Results are shown in Table II.

Table II. Energy Dependence of 3914-Å Cross Sections with Photometer No. 2

Electron Energy (eV)	Nitrogen Pressure P(μ Hg)	Beam Current I(mA)	Tube Current i(10^{-10}A)	Cross Sections Q(10^{-17} cm^2)
95	0.44	0.058	0.091	1.53
196	0.44	0.170	0.227	1.30
399	0.44	0.38	0.377	0.98
501	0.52	0.80	0.81	0.84
602	0.44	0.43	0.328	0.75
907	0.44	1.01	0.57	0.55
1211	0.44	2.02	0.94	0.45
1516	0.44	2.02	0.80	0.39
1820	0.44	2.50	0.84	0.33
2023	0.44	3.02	0.97	0.31

With photometer No. 2, pressure dependence was observed at electron energies of 196, 501, 907, and 1820 eV. Light output was proportional to N_2 pressure over the range 0.1 to 1.0 μ Hg.

Spectrometer Measurements

With beam current and pressure held constant, the signal from the photomultiplier tube at the exit slit was recorded, while the spectrometer scanned across the 3914-Å band. Though the rotational lines were not resolved, the band contours appeared "normal," i.e., about as expected for thermal equilibrium near room temperature. The 3884-Å (1,1) first negative band is resolved, and appears to be ~ 5% of the 3914-Å band intensity. Its contribution to the photometer signals must be less than 1%.

The photomultiplier signal, integrated over wavelength across the band, can be related to the

excitation cross section by the equation

$$Q = \frac{4\pi J}{I N E_\lambda T_v} \frac{R_\lambda h_n}{i_\lambda} \frac{R_2}{R_1} \frac{W_n^0 W_x^0}{W_n W_x},$$

where I, N, E_λ, and T_v have the same significance as above, and where

J = spectrometer signal integrated over the band (A-Å)

$\frac{i_\lambda}{R_\lambda h_n}$ = spectrometer sensitivity, as shown in Fig. 2.

R_1 = distance, beam to mirror = 78.5 cm

R_2 = distance, mirror to slit = 26.5 cm

W_n^0, W_x^0 = entrance and exit slit widths in the calibration = 100 μ

W_n, W_x = slit widths in the observation = 100 μ or 200 μ

Results of the spectrometer observations for the 3914-Å band are shown in Table III. For these observations

$$E_\lambda = 3.17 \text{ eV},$$

$$W_n, W_x = 200\ \mu,$$

and

$$\frac{i_\lambda}{h_n R_\lambda} = 2.82 \times 10^{-2} \text{ (3914 Å, second order)}.$$

The cross section

$$Q = \frac{J \text{ (A-Å)}}{I \text{ (A) } P\ (\mu)} \times 3.52 \times 10^{-12} \text{ (cm}^2\text{)}.$$

Table III. Energy Dependence of the 3914-Å Band Cross Sections with Scanning Spectrometer

Electron Energy (eV)	Nitrogen Pressure P(μ Hg)	Beam Current I(mA)	Integrated Signal J(10^{-10} A-Å)	Cross Sections Q(10^{-17} cm²)
95	0.43	0.070	1.28	1.50
196	0.50	0.21	3.72	1.25
501	0.43	0.55	5.82	0.86
907	0.43	1.36	9.06	0.54
1820	0.50	2.55	11.50	0.32
2023	0.43	2.19	7.92	0.30

With the scanning spectrometer, the dependence on beam current of the integral over the 3914-Å band was observed for 907-eV electron energy and 0.56-μ pressure. The band intensity was proportional to current from 0.02- to 2.0-mA beam current.

At the same energy (907 eV) and pressure (0.56 μ), the cross sections for other v' = 0 N_2^+ first negative bands were determined. They are:

(0,1)	4278 Å	1.8×10^{-18} cm²,
(0,2)	4709 Å	4.1×10^{-19} cm²,
(0,3)	5228 Å	7.0×10^{-20} cm².

Summary and Comments

The pressure and current dependence indicate no appreciable contribution from secondary processes. There is no indication in the spectral observations of a contribution at 3914 Å due to features other than the (0,0) band. The relative emission probabilities of the (0,0), (0,1), (0,2), and (0,3) bands, measured primarily as a check on the spectrometer calibration, were 1.00, 0.33, 0.075, and 0.013, in agreement with values of 1.00, 0.35, 0.08, and 0.01 derived from the data of Wallace and Nicholls.[16]

The electron excitation cross-section data for the 3914-Å band of the N_2^+ first negative system are collected and averaged in Table IV.

Table IV. 3914-Å Band Electron Excitation Cross Sections (10^{-17} cm²)

Electron Energy (eV)	Photometers No. 1	Photometers No. 2	Spectrometer	Average
95	1.48	1.53	1.50	1.50
196	1.35	1.30	1.25	1.30
399		0.98		0.98
501	0.89	0.84	0.86	0.86
602		0.75		0.75
907	0.55	0.55	0.54	0.55
1211		0.45		0.45
1516		0.39		0.39
1820	0.34	0.33	0.32	0.33
2023		0.31	0.30	0.31

It is worth mentioning that initial values, which received limited circulation in a preliminary report, were about 15% higher than those presented here. The difference was evidently due partly to a poor photometric calibration in the initial measurements, but ~ 5% contribution was due to light scattered from the slit body of an ultraviolet spectrometer.

The agreement among the three sets of values in Table IV is better than that of all numbers obtained. Maximum "scatter" in measurements (including pressure and current dependence) with all instruments was about ± 10% of the average values shown. The absolute accuracy estimated for the measurement of 3914-Å band intensity is ± 6%. The same accuracy is claimed for the pressure measurement. The beam current is thought to be accurately measured to within ± 2% for electron energies above 200 eV, ± 4% near 200 eV, and ± 6% near 100 eV. A conservative estimate for the maximum uncertainty is thus ± 20% below 200 eV and ± 15% above 200 eV.

Comparison with Other Experiments

The ratio of the N_2 total-ionization cross sections to the 3914-Å cross sections is of some interest. This ratio is thought to be constant over a wide energy range. Other cross-section measurements indicate nearly constant ratios within various energy intervals ranging from 50 eV to 20 keV,[5,7-9,12] though the actual magnitude of the ratios depends on which set of ionization and excitation cross sections are used.

In Table V, the ratios of N_2 ionization cross sections of Tate and Smith[17] (TS), Rapp and Englander-Golden[18] (RE), and Schram, de Heer, van der Wiel, and Kistemaker[19] (SHWK) to the 3914-Å cross sections from Table IV are shown. The excitation and ionization cross sections are in constant proportion within about ± 5% over the range 100 to 2000 eV. Provided the proportionality extends to higher energy, one can compare the excitation cross sections in Table IV with others obtained at higher energy by comparing their magnitudes relative to the ionization cross sections.

Ratios such as those in Table V are sometimes used, with the average electron energy loss per nitrogen ion (generally taken as 35 eV) to calculate efficiencies for the production of 3914-Å photons when energetic electrons "run down" in nitrogen or air (see, for example, Refs. 9 and 12). Making the usual assumptions, values obtained for the 3914-Å efficiency in air based on averages in Table V are, respectively, 3.8×10^{-3} (TS), 4.2×10^{-3} (RE), and

Table V. Ratio of N_2 Total Ionization Cross Sections to 3914-Å Excitation Cross Sections

Energy (eV)	Ratio TS[17]	RE[18]	SHWK[19]
95	19.2	16.7	
196	19.7	17.6	
399	18.6	16.9	
501	18.1	16.9	
602	18.3	17.2	15.3
907		17.8	15.3
1211			15.1
1516			14.6
1820			15.2
2023			14.8
Averages	18.8	17.2	15.0

4.8×10^{-3} (SHWK). The mean is 4.3×10^{-3} which may be compared with the value 3.4×10^{-3} measured by Hartman and Hoerlin[10] at this Laboratory and recently confirmed by Hartman.[11] One may note also that a most probable 3914-Å fluorescence efficiency of 1% was derived by Bennett[20] and Hoerlin[21] from observations of the emission produced by x rays from high altitude nuclear explosions.

The calculation for the efficiency derived from laboratory data uses measured values of ionization efficiency and ionization cross sections, as well as the 3914-Å excitation cross sections, all of which have some uncertainty. It is based on the assumption that the ratio of the number of nitrogen ions to the number of 3914-Å photons produced is independent of the energy of exciting electrons over the important energy range. While one must therefore not give too much weight to the calculated efficiency, it is in fair agreement with the efficiency measured in the laboratory. With some reservation, this may be taken as a confirmation that in the laboratory efficiency experiment each excitation of the parent state of the 3914-Å band is produced by a single collision of an electron with N_2 in the ground state. With similar reservation, one may conclude that the efficiency in the high altitude explosions is higher due to excitation by other processes. This is presumably because such a large air mass is excited by the explosion and because so much energy is deposited

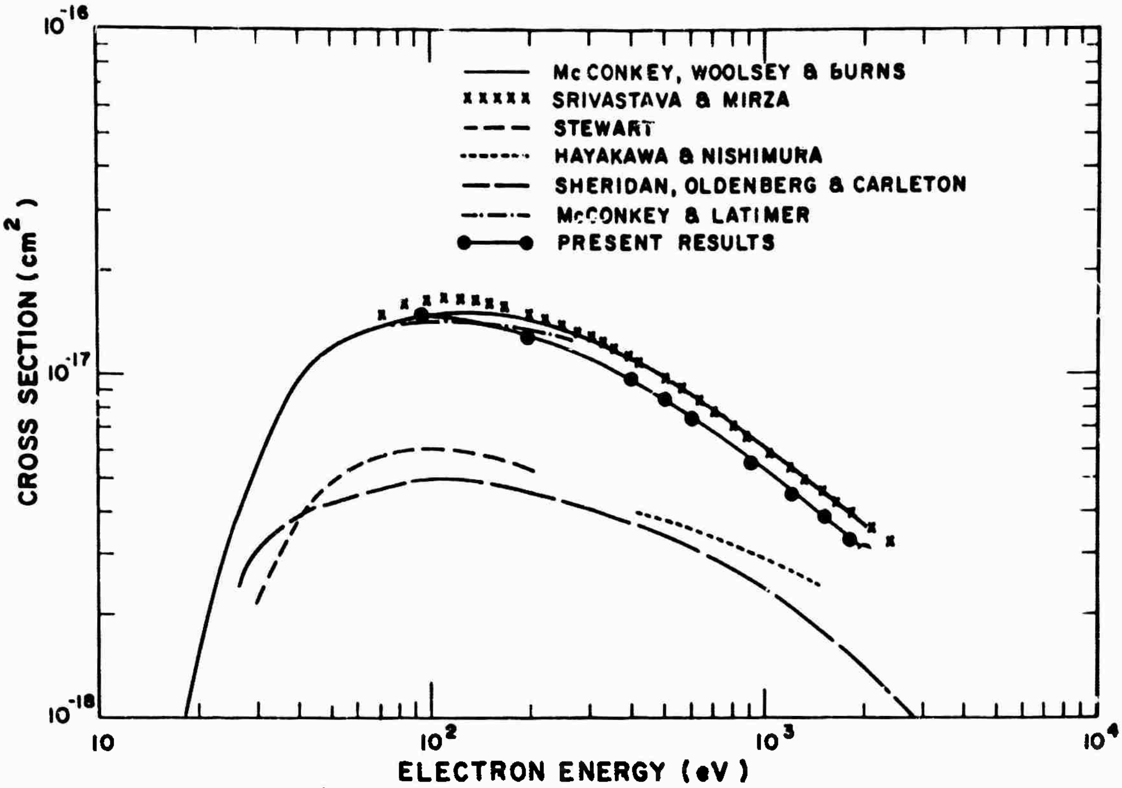

Fig. 3. Comparison of 3914-Å excitation cross sections with those reported by others (Refs. 2-4, 6-8).

so rapidly that other processes are more important than in the laboratory experiment.

The 3914-Å cross sections are compared with results of other cross-section measurements in Fig. 3. The agreement with Srivastava and Mirza[7] is good; the difference is less than 15% in the common energy range. The agreement with McConkey and Latimer[6] is very good in the narrow range of overlap. The later work of McConkey, Woolsey, and Burns[8] is also in good agreement with ours. The difference between the present results and those of Stewart;[2] Sheridan, Oldenberg, and Carleton;[3] and Hayakawa and Nishimura[4] is considerable. Our values are greater by ratios of 1.5 to 3.

Published cross sections of Davidson and O'Neil[5] are in agreement with Sheridan et al.,[3] and, by inference, also in disagreement with the values in Table IV. Results of a recent measurement by O'Neil and Carleton will be discussed briefly in the next section.

Cross Checks

After our initial measurements, the disagreement with the early work was discussed with Dr. N. P. Carleton of the Smithsonian Astrophysical Observatory, who participated in one of the earlier experiments.[3] It was partly because of his suggestions that additional photometer calibrations were performed and spectrometer measurements were made. He also suggested that we compare equipment in the hope of resolving the difference in our results. Mr. R. O'Neil of American Science and Engineering expressed interest in an exchange for similar reasons. After the measurements described above, joint cross-check measurements with O'Neil and Carleton were undertaken.

Carleton and O'Neil ascertained that their radiometry standards were in agreement, and compared pressure gauges. O'Neil visited LASL bringing Carleton's Pirani gauge, an NBS-calibrated pyrometer used at ASE, some small standard apertures, and a photomultiplier and 3914-Å interference filter to construct a photometer. We cooperated in the following measurements.

The Pirani gauge was calibrated with our McLeod gauge at 3.19 and 1.39 μ Hg. The two previous calibrations of the gauge in Massachusetts had indicated pressures 4% and 10% higher (O'Neil) and 13% and 19% higher (Carleton), respectively, than the McLeod gauge.

The pyrometer was checked against our brightness temperature standard lamp G-25155a (the lamp used in the spectrometer calibration). For readings in the range 2100 to 2400° K, the pyrometer consistently indicated temperatures 10° to 15° higher than those derived from the lamp calibration, corresponding to 8 to 12% higher radiance at 3914 Å.

In O'Neil's photometer calibration method, the 3914-Å photometer looks at a small aperture of known area, behind which is the ribbon filament of a tungsten lamp. The filament temperature is measured by the pyrometer, and the radiant flux at the photometer is calculated. From the photometer signal and the filter transmission, the sensitivity for the 3914-Å band is determined. A similar calibration was performed for photometer No. 1 and O'Neil's photometer, except that the lamp temperature was determined by setting the current. The calibration was based primarily on measurements at 2200° K (brightness). The sensitivity of the tube in photometer No. 1 was 1.37×10^3 A/W at 3914 Å, in good agreement with the value of 1.31×10^3 A/W obtained by another method.

The two photometers were used to make a 3914-Å cross-section measurement at 907-eV electron energy, and 1.39 μ pressure (determined by setting an ionization gauge at the reading recorded during the Pirani gauge calibration). Results with the ASE photometer and photometer No. 1 were, respectively, 4.6×10^{-18} cm² and 4.9×10^{-18} cm², using the calibrations just obtained. Using the original calibration of photometer No. 1, the cross section would be 5.1×10^{-18} cm². The LASL average value at 907 eV is 5.5×10^{-18} cm².

Apparently, if the Pirani gauge with the ASE calibration had been used to measure pressure, and the pyrometer had been used to measure temperature in the photometer calibration, the ASE photometer would have indicated about the same cross section of 4.6×10^{-18} cm²; thus, the difference in cross sections should indicate the net difference introduced by radiometry and pressure-gauge calibrations at LASL and ASE, no more than 10 to 15%. The pressure-gauge calibration might explain a difference of 20% between our results and those of Carleton.

O'Neil and Carleton[22] have recently made observations on the 3914-Å emission produced by 8- and 50- keV electrons. Further observations are necessary to reach firm conclusions; however, these preliminary measurements indicate cross sections appreciably higher than those obtained in the older measurements with the same electron energies,[5,3] and more nearly consistent with cross sections measured here at lower energies.

CONCLUSIONS

The LASL measurements, together with those of Srivastava and Mirza,[7] McConkey et al.,[6,8] and the observations of O'Neil and Carleton,[22] provide considerable evidence that the 3914-Å electron excitation cross sections are higher than the values obtained in the earlier experiments.[2-5] The reproducibility of results obtained here under a variety of conditions, and using different photometric techniques, allows some confidence that the cross sections presented are correct within the quoted accuracy.

ACKNOWLEDGMENTS

The author thanks H. Hoerlin for suggesting the experiment, and for his advice. The assistance of W. Gould in the photometric calibrations is gratefully acknowledged. Thanks are due to N. P. Carleton for his interest and advice, and to him and R. O'Neil for initiating and cooperating in the cross-check measurements at LASL and Cambridge. The author is pleased to acknowledge communications with B. N. Srivastava and J. W. McConkey, and appreciates the receipt of preprints of their publications. He also appreciates helpful discussions with W. B. Maier, M. Peek, P. Hartman, and others in Group J-10. The work was conducted under the auspices of the AEC and sponsored by the Advanced Research Projects Agency of the Department of Defense.

REFERENCES

1. D. R. Westervelt and H. Hoerlin, Proc. IEEE 53, 2067 (1965).
2. D. T. Stewart, Proc. Phys. Soc. 69, 437 (1956).
3. W. F. Sheridan, O. Oldenberg, and N. P. Carleton, Abstr. 2nd Intern. Conf. Phys. Electronic and Atomic Collisions, Boulder, Colorado, 1961.
4. S. Hayakawa and H. Nishimura, J. Geomag. Geoelect. (Japan) 16, 72 (1964).
5. G. Davidson and R. O'Neil, Abstr. IVth Intern. Conf. Phys. Electronic and Atomic Collisions, Quebec, 1965.
6. J. W. McConkey and I. D. Latimer, Proc. Phys. Soc. 86, 463 (1965).
7. B. N. Srivastava and I. M. Mirza, Trans. Am. Geophys. Un. 48, 73 (1967); also Phys. Rev. (to be published).
8. J. W. McConkey, J. M. Woolsey, and D. J. Burns, Planet. Space Sci. 15, 1332 (1967).
9. A. Dalgarno, I. D. Latimer, and J. W. McConkey, Planet. Space Sci. 13, 1008 (1965).
10. P. L. Hartman and H. Hoerlin, Bull. Am. Phys. Soc. 11, 69 (1962); also P. L. Hartman, Los Alamos Scientific Laboratory report LA-3147-MS, January 1964.
11. P. L. Hartman, Los Alamos Scientific Laboratory report LA-3793, August 1967.
12. G. Davidson, Planet. Space Sci. 14, 651 (1966).
13. J. C. de Vos, Physica 20, 669, 690 (1954).
14. P. E. Carr, Vacuum 14, 37 (1964).
15. H. H. Poigurski and F. N. Davis, Vacuum 10, 377 (1960).
16 L. V. Wallace and R. W. Nicholls, J. Atmospheric Terrest. Phys. 7, 101 (1955).
17. J. T. Tate and P. T. Smith, Phys. Rev. 39, 270 (1932).
18. D. Rapp and P. Englander-Golden, J. Chem. Phys. 43, 1464 (1965).
19. B. L. Schram, F. J. DeHeer, M. J. Van der Wiel, and J. Kistemaker, Physica 31, 94 (1965).
20. E. W. Bennett, Los Alamos Scientific Laboratory report LA-3409-MS, June 1965 (SRD); and E. W. Bennett and R. F. Holland, LA-3409-MS Supplement, Sept. 1965 (U).
21. H. Hoerlin, Los Alamos Scientific Laboratory report LA-3417-MS, April 1965.
22. R. O'Neil and N. P. Carleton, personal communication, June 1967.